

## Final Report for NASA Grant NAG 5-2506

## Multiwavelength Blazar Studies

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## 1.0 Overview

The discovery of a multitude of strongly gamma-ray emitting AGNs by EGRET and the detection of at least two AGNs at even higher energies by the Whipple Collaboration generated much interest in the study of those objects and extensive observations were conducted in the following years. The Michigan group concentrated its effort on continued observations of the two TeV gamma-ray sources, Markarian 421 and Markarian 501, to monitor variability in the high energy emission as well as to provide simultaneous measurements during multiwavelength observations of these objects.

## 2.0 Markarian 421

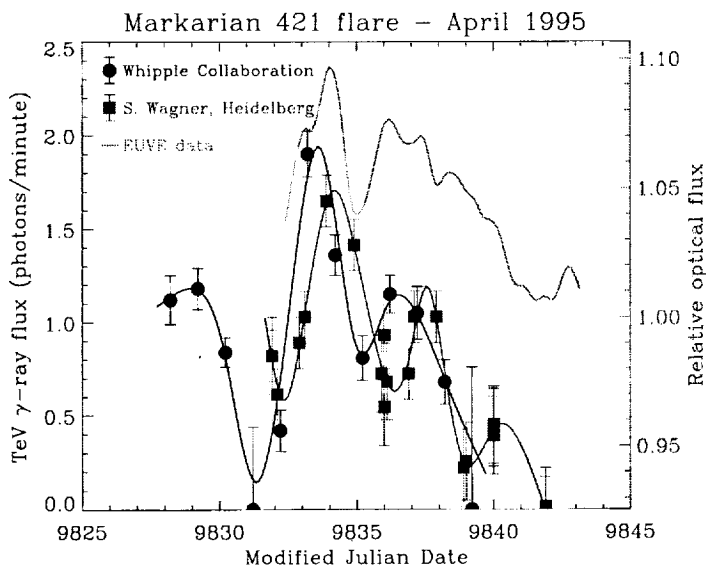
In 1992, the blazar Markarian 421 became the first extragalactic object detected at TeV energies. Soon after the initial discovery, it was observed that the flux levels occasionally varied considerably from the time average. After continued observation of the source and careful analysis of the data to exclude possible instrumental effects, we concluded that rapid variations of an order of magnitude in intensity on time scales of about one day were quite real. Since that time, the source has been extensively monitored and has been observed to flare at time scales as short as 1 hour with flare amplitudes of more than 10 times the average emission.

Strong variability in the emission from some AGN had also been observed by the EGRET instrument and by previous X-ray and UV missions. Common properties of highly variable AGN are strong radio emission and hard radio spectra and the observational similarities have led to the classification of this class as blazars. There is little consensus on the correct blazar emission model but it has been widely recognized that simultaneous monitoring of flaring activity across the emission band can provide a powerful tool to extract information about the processes involved in the production of the observed high energy radiation. Our effort concentrated on studying the correlation of the relative phase and amplitude between the TeV emission and the lower frequencies.

Prominent TeV outbursts were observed on several occasions during which measurements at other wavelengths were scheduled. In 1994, a TeV flare occurred in which the flux above 250 GeV increased by nearly a magnitude above quiescent levels. This TeV outburst overlaps EGRET observations which show no significant change in the GeV emission. This flare also coincided with observations made in the UV, IR, mm, radio and X-ray bands. While the X-ray observations made with the ASCA satellite showed the source to be in a flaring state, observations made at the other wavelengths revealed little sign of enhanced activity. These

observations are summarized in Macomb et al. (1995).

A multiwavelength campaign in 1995 showed strong correlations between the variation in the TeV flux and the X-ray, EUV, and optical flux (figure). This observation suggests that the optical emission lags the higher energy photons in contrast to the expectation of inverse-Compton models which assume an interaction of high energy electrons with pre-existing photons (from synchrotron radiation).



*Figure 1: Comparison of the observed emission in the optical, UV, and at TeV gamma-ray energies for the April 1995 flare of Markarian 421.*

This observation also allowed constraint of the relativistic Doppler factor of the TeV gamma rays to values larger than previously set by X-ray observations. Simultaneous observations with the EGRET instrument during this time revealed no change in the MeV flux, constraining AGN models which predict equal flare amplitudes at all gamma-ray energies.

## 2.1 Markarian 501

In 1995, a second TeV AGN, Markarian 501, was discovered by the Whipple Collaboration during a program which focused on observations of blazars similar to Markarian 421. This object was not detected by the EGRET instrument. The average level of emission at TeV energies is about 20% that of the Markarian 421 flux and thus falls below the EGRET sensitivity threshold. Like Markarian 421, the source shows strong evidence for day scale variability. This observation came somewhat as a surprise because previous X-ray and optical observations of Markarian 501 did not show variations in the flux on these short time scales.

## Publications

“Multiwavelength Observations of Markarian 421 During a TeV/X-Ray Flare”, D.J. Macomb, C.W. Akerlof, H.D. Aller, M.F. Aller, D.L. Bertsch, F. Bruhweiler, J.H. Buckley, D.A.

Carter-Lewis, M.F. Cawley, K.-P. Cheng, C. Dermer, D.J. Fegan, J.A. Gaidos, W.K. Gear, C.R. Hall, R.C. Hartman, A.M. Hillas, M. Kafatos, A.D. Kerrick, D.A. Kniffen, Y. Kondo, H. Kubo, R.C. Lamb, F. Makino, K. Makishima, A. Marscher, J. McEnery, I.M. McHardy, D.I. Meyer, E.M. Moore, E. Ramos, E.I. Robson, H.J. Rose, M.S. Schubnell, G. Sembroski, J.A. Stevens, T. Takahashi, M. Tashiro, T.C. Weekes, C. Wilson, and J. Zweerink, *Astrophys. J.* **449**, L99 (1995).

“Detection of Gamma Rays with  $E > 300$  GeV from Markarian 501”, J. Quinn, C.W. Akerlof, S. Biller, J. Buckley, D.A. Carter-Lewis, M.F. Cawley, M. Catanese, V. Connaughton, D.J. Fegan, J.P. Finley, J. Gaidos, A.M. Hillas, R.C. Lamb, F. Krennrich, R. Lessard, J.E. McEnery, D.I. Meyer, G. Mohanty, A.J. Rodgers, H.J. Rose, M.S. Schubnell, G. Sembroski, T.C. Weekes, C. Wilson, and J. Zweerink, *Astrophys. J.* **456**, L83 (1996).

“Very High Energy Gamma-Ray Emission from the Blazar Markarian 421”, M.S. Schubnell, C.W. Akerlof, S. Biller, J. Buckley, D.A. Carter-Lewis, M.F. Cawley, M. Chantell, V. Connaughton, D.J. Fegan, S. Fennell, J. Gaidos, A.M. Hillas, A.D. Kerrick, R.C. Lamb, D.I. Meyer, G. Mohanty, H.J. Rose, A.C. Rovero, G. Sembroski, T.C. Weekes, C. Wilson, and J. Zweerink, *Astrophys. J.* **460**, 644 (1996).

“Gamma-Ray Variability of the BL Lacertae Object Markarian 421”, J.H. Buckley, C.W. Akerlof, S. Biller, D.A. Carter-Lewis, M. Catanese, M.F. Cawley, V. Connaughton, D.J. Fegan, J.P. Finley, J. Gaidos, A.M. Hillas, J.F. Kartje, A. Königl, F. Krennrich, R.C. Lamb, R. Lessard, D.J. Macomb, J.R. Mattox, J.E. McEnery, G. Mohanty, J. Quinn, A.J. Rodgers, H.J. Rose, M.S. Schubnell, G.L. Sembroski, P.S. Smith, T.C. Weekes, C. Wilson, and J. Zweerink, *Astrophys. J.* **472**, L9 (1996).

“Detection of Gamma Rays with  $E > 100$  MeV from BL Lacertae”, M. Catanese, C.W. Akerlof, S.D. Biller, P. Boyle, J.H. Buckley, D.A. Carter-Lewis, M.F. Cawley, V. Connaughton, B.L. Dingus, D.J. Fegan, C.E. Fichtel, J.P. Finley, J.A. Gaidos, W.K. Gear, R.C. Hartman, A.M. Hillas, F. Krennrich, R.C. Lamb, R.W. Lessard, Y.C. Lin, J.E. McEnery, A.P. Marscher, G. Mohanty, R. Mukherjee, J. Quinn, E.I. Robson, A.J. Rodgers, H.J. Rose, F.W. Samuelson, G. Sembroski, M.S. Schubnell, J.A. Stevens, H. Teräsranta, D.J. Thompson, T.C. Weekes, C. Wilson, and J. Zweerink, *Astrophys. J.* **480**, 562 (1997).